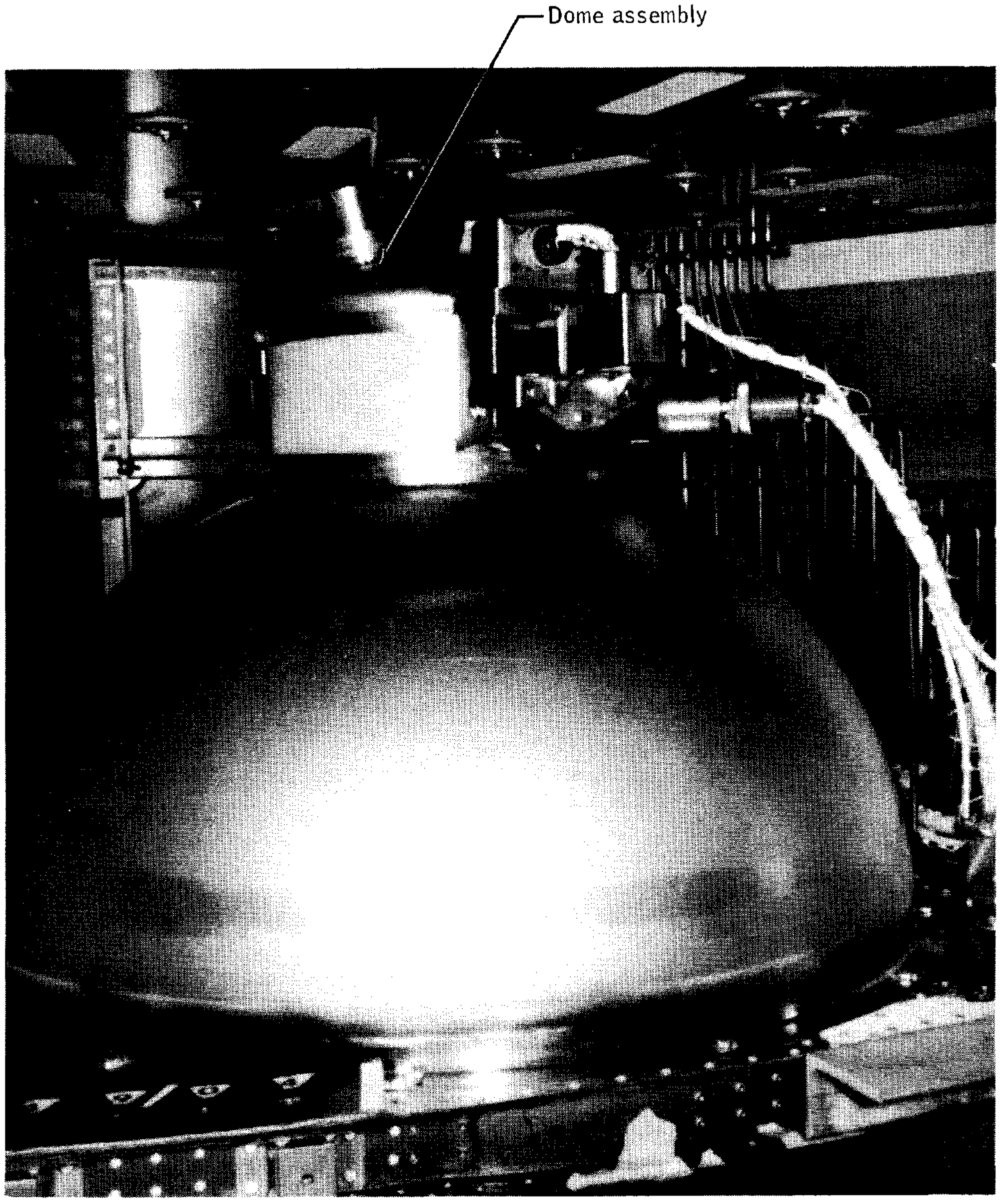

Figure D3-20.- Oxygen shelf showing location of tank dome assemblies.

the dome contains the upper pinch-off tube, through which the annulus is evacuated, and a burst disc (rated at 75 psi ± 7.5 psi) that provides burst protection for the outer shell in the event of leakage from the inner shell into the annulus. The arrangement of the fluid lines and electrical conduit within the dome is shown in figures D3-21 and D3-22. The coiling of these lines provides the high impedance path for heat leaks between the inner and outer shells of the tank. In the case of the large diameter vent line, this path is made longer by use of a double-walled tube outside the dome, with connection between inner and outer walls at the extremity of the projection of the tube from the tank.

Tube sizes are listed as follows (all dimensions in inches):

Oxygen Tank Tube Sizing

Vent tube	1/2 OD x 0.015 wall (inside coil cover) 3/4 OD x 0.028 wall (outside coil cover) Inconel 750 AMS 5582
Fill tube	3/8 OD x 0.022 wall Inconel 750 AMS 5582
Feed tube*	1/4 OD x 0.015 wall Inconel 750 AMS 5582
Electrical tube	1/2 OD x 0.015 wall Inconel 750 AMS 5582
Vapor-cooled* shield tube	3/16 OD x 0.015 wall Inconel 750 AMS 5582
Pressure vessel to vapor* cooled-shield tube	1/4 OD x 0.015 wall Inconel 750 AMS 5582

*These three tubes are joined sequentially to provide a single feed line which is looped around the tank inner shell to provide regenerative cooling for the vessel.

A total of 18 wires pass through the electrical conduit, eight AWG no. 26's, four AWG no. 22's, and six AWG no. 20's. The conduit is shown in figure D3-23. At the start of the investigation some members of the Panel felt that the unorthodox detanking procedure used at KSC could have resulted in unacceptably high temperatures in this electrical conduit due to resistive heating of the heater wires. This possibility is discussed in a later section.

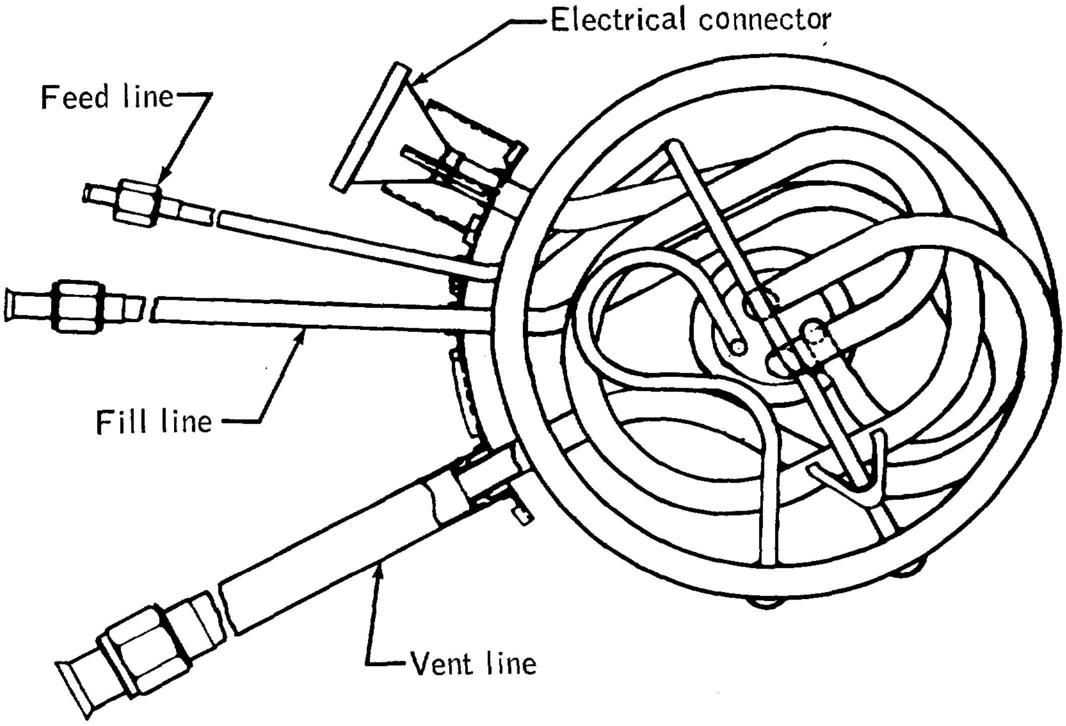

Figure D3-21.- Arrangement of tubing within tank dome assembly.

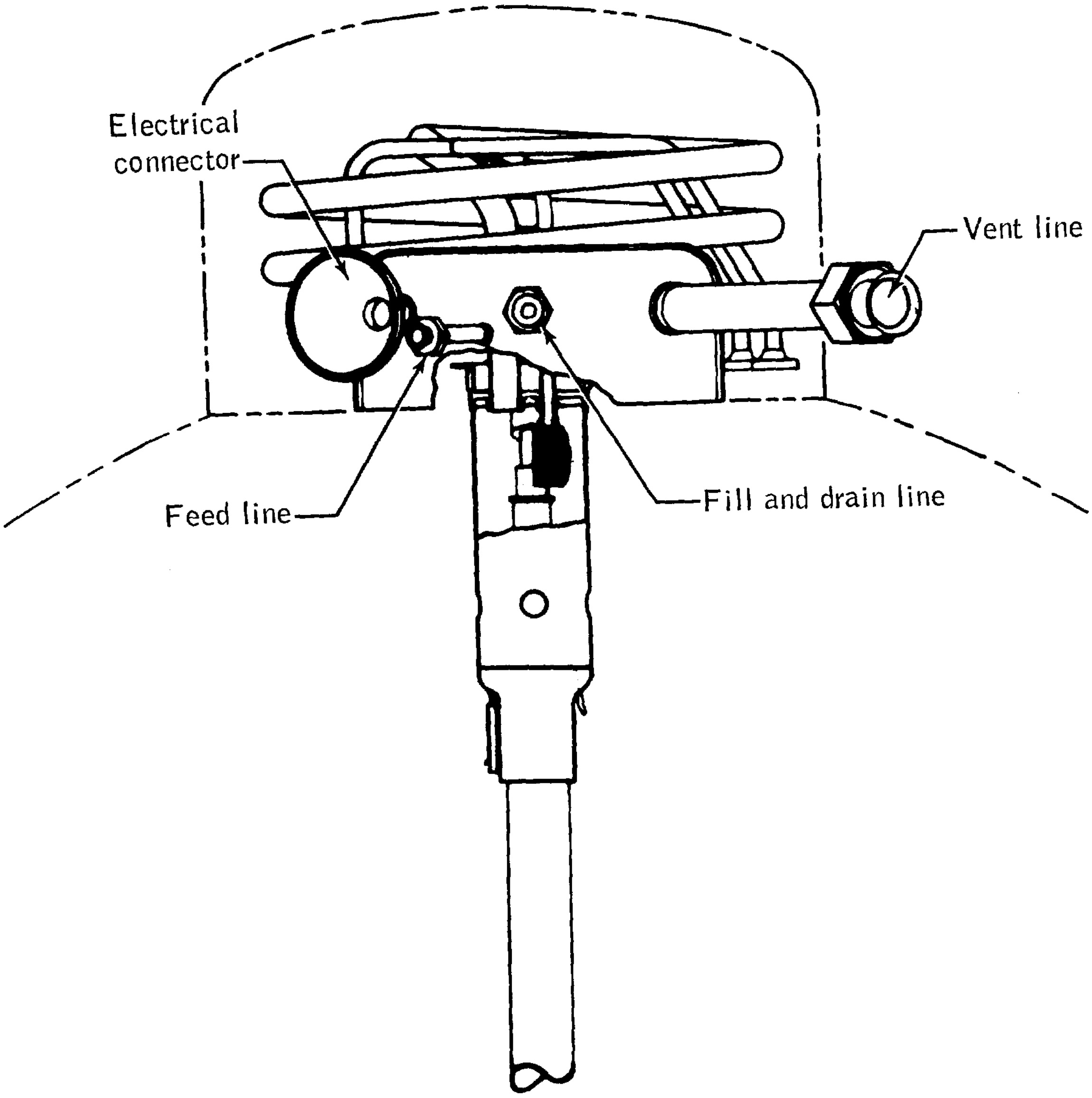

Figure D3-22.- Arrangement of tubing within tank dome assembly.

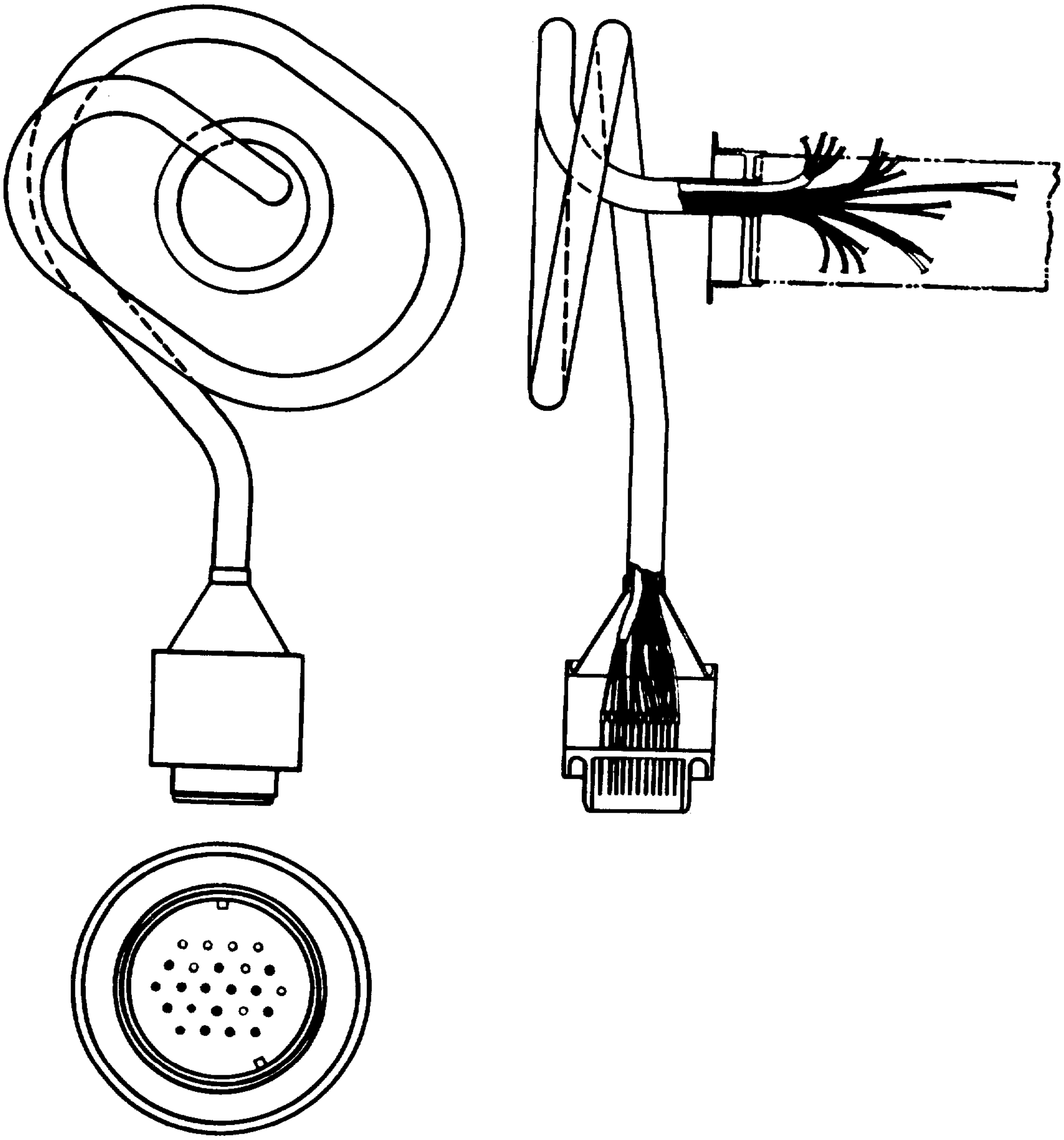

Figure D3-23.- Arrangement of electrical conduit.

The design of this portion of the tank results in a configuration in which it is not possible to perform visual inspection of wiring after assembly. In consequence, the possibility of damage, in many cases undetectable by normal quality assurance procedures, is significant.

Filter

The filter, which is welded onto the supply line projection into the tank, is located within the top of the quantity gage adapter when the tank is assembled. It consists of a series of thin washers stacked on a tube-like mandrel containing relatively large holes communicating with the interior of the tube. The washers have a series of raised projections on one surface arranged in concentric circles. The projections in each circle are staggered with respect to those adjacent circles. When stacked on the mandrel, the spacing between the washers provided by the projections present a tortuous path for the fluid to traverse in order to enter the center of the mandrel and thus provides a filtering action. The filter is rated at 175 microns and is intended to prevent particles greater than this size from entering the feed line.

The filter is of simple and reliable construction, and should provide only very small restriction to flow out of the tank. In the application, the two components protected by the filter are the relief valve and the check valve in the tank no. 2 valve module, both of which have moving poppets that must seat properly in order not to leak.

In normal circumstances the filter location is appropriate. Under abnormal circumstances, such as the combustion in tank no. 2 experienced on Apollo 13, the filter might become clogged with solid combustion products and thus preclude flow to the relief valves. Considering its construction, and ample flow area, this is not very probable. Tests are to be conducted to verify this.

Caution and Warning Provisions

Because of their design, the caution and warning system and the switch-controlled indicators ("talkbacks") did not present correct systems status to the crew during the Apollo 13 accident. As described in Appendix B, the following items are noted as examples:

1. The loss of oxygen to fuel cells 1 and 3 occasioned by closure of the oxygen shutoff valves was not indicated. The series logic used in the information system required that both the hydrogen shutoff valve and the oxygen shutoff valve be closed to activate the warning system. Simultaneous operation of the valves is appropriate to a deliberate shutdown of a fuel cell which should require no warning indication.

2. The crew was not alerted to the abnormal rise and subsequent loss of oxygen pressure in tank no. 2 because a normal out-of-limits operational signal (low hydrogen pressure) was in existence.

3. When power was lost to main bus B, the "talkback" indicators designed to indicate the state of RCS valves were no longer energized and could not properly indicate valve position.

Thus, accurate information as to the state of spacecraft systems, which is vital in time of emergency, was not provided by the caution and warning system.

ABNORMAL EVENTS IN THE HISTORY OF THE OXYGEN TANK

The oxygen tank which failed during the Apollo 13 mission had been subjected to two abnormal incidents prior to launch. The first occurred during spacecraft assembly. The oxygen shelf was "dropped" and the tank subjected to a shock load. The second abnormal condition occurred at KSC. An unorthodox detanking technique was used when the tank failed to empty during the normal procedures. The possible consequences of those incidents are discussed in the following sections.

Oxygen "Shelf Drop" Incident

The oxygen shelf which flew in Apollo 13 (Spacecraft 109) originally was installed in Spacecraft 106. On October 21, 1968, this shelf was in process of being removed from Spacecraft 106 for a rework of the vac-ion pumps. During the removal, the sling adapter (ground equipment) broke. The cause for the failure was traced to failure to remove one of the bolts attaching the shelf to the service module. At the time of the incident, it was assumed that the failure permitted the shelf outboard edge to fall back about 2 inches, at which point the shelf motion was stopped by the supports in the service module. An analysis of the stiffness of the oxygen shelf led to the prediction of a shock load of the order of 10g. The incident is reported in more detail in Appendix C. An analysis of the incident is contained in the files of the Board. The general conclusions are as follows:

1. The Apollo 13 oxygen "shelf drop" incident can be explained by assuming that the counterbalance weights on the 9EH-1275-100 sling were run out in an attempt to "balance" the effect of the shelf attach bolt (which was inadvertently not removed) to a point at which they caused the sling adapter to fail in bending.

2. The geometry and loading of the system at the time of failure would rotate the oxygen shelf about the remaining shelf attach bolt until the top of oxygen tank no. 2 impacted the underside of the fuel cell shelf, causing the observed dent in the shelf.

3. Tests to reproduce the dent in the fuel cell shelf have been conducted by striking a specimen of the shelf aluminum honeycomb material with an appropriately weighted tank pinch-off tube cover. The test results indicate that in order to reproduce the observed dent, a maximum acceleration of 7g was required.

4. On the basis of these data, it does not appear that the loads transmitted to the internal components of the tank during the "shelf drop" incident were of sufficient magnitude to cause any structural failure. One possible effect, however, could have been the displacement of a marginally secured connection between the fill line and the inner element of the quantity gage capacitor. Should this have occurred, it could have been the cause of the detanking anomaly experienced at KSC with oxygen tank no. 2 during the preflight operations on Apollo 13.

Detanking at KSC

The difficulty with the detanking of oxygen tank no. 2 subsequent to the countdown demonstration test (CDDT) is described in Appendix C. As noted in the preceding section, the inability to detank may be ascribed to a displacement of the short Inconel tube in that portion of the fill line located in the top of the quantity probe or the absence of this tube. Tests conducted at Beech Aircraft Corporation subsequent to the flight have demonstrated that if the tube is displaced laterally about 0.090 inch from its mating Teflon adapter, it is not possible to detank in normal fashion. The manufacturing tolerances for this subassembly have been discussed previously, and it is apparent that it is possible for such a displacement to occur if the parts are at appropriate extremes of the tolerances.

The nonstandard procedure used to detank oxygen tank no. 2 involved continuous power application to the heaters at GSE power supply voltage for 8 hours and 10 minutes. The fans were operated for all but the first hour and 20 minutes of this period. There is no conclusive evidence that either of the thermostats ever operated to open the heater circuits during this period. This occurred, despite the fact that the tank temperature sensor output, indicating ullage space temperature under the conditions of this procedure, was still rising when the instrument reached its readout limit of 84° F.

During this detanking, the GSE power supply was providing approximately 6.0 amperes to each of the two heaters at approximately 65 V dc at the spacecraft. Tests conducted at MSC subsequent to the flight showed that when a thermostat attempted to interrupt a 6.0-ampere current at 65 V dc, the contacts welded shut. Whereas such contacts are rated by the manufacturer to interrupt at least a 6-ampere alternating current, under direct current conditions a considerable arc will be drawn and welding of the contacts will frequently result. At the time of this writing, three thermostats have been tested under voltage and current conditions like those experienced during the nonstandard detanking. All three failed by welding closed. Were the contacts in oxygen tank no. 2 thermostats to have failed in this manner, which seems highly probable, the heaters would have drawn current for the total period that the circuits were energized. There are a number of possible consequences of this condition. These are discussed in the following paragraphs.

Because the wiring in the conduit in the tank dome is of relatively small diameter for the current carried, it might lead to excessive wire temperatures by resistance heating, as this conduit represents a stagnant region with poor heat paths for removal of the heat generated. Were the temperatures to rise sufficiently, it could degrade the insulation to the point that the wire might be exposed. Preliminary calculations indicated that the temperature of the wires might rise to the point of insulation degradation and/or melting of soldered connections. A preliminary test using an actual conduit has indicated the temperature would not rise above about 325° F, which is well below the threshold temperature for wire insulation and solder damage. More definitive data on this possibility will be provided by a test planned for the near future at Beech Aircraft Corporation. A flight-type tank will be subjected to a reproduction of the nonstandard detanking process to determine, among other things, how hot the wiring in the conduit would get.

The second possible mode for damaging the wiring during the detanking is related to the pressure pulsing employed during the latter part of the detanking operation. When the tank is pressurized and quickly vented, the cryogenic oxygen will boil violently, probably producing "slugging" or "geysering" at the liquid-vapor interface. This action could easily flex the large unsupported loop of wire that results from the assembly process and thus could induce mechanical damage to the wire. This, too, must be confirmed by test before it can be considered as more than a possibility.

The third possibility for inducing wire damage applies primarily to the wiring in proximity to the heaters--especially the fan motor leads that are routed through the 12 inches of 3/16-inch diameter conduit that runs internal to the heater probe (see fig. D3-16). If the thermostat contacts failed by welding closed, as seems probable from the results of the thermostat tests described earlier, the heater probe metal temperatures would continue to rise, limited only by the heat balance between that being generated by the heater and that being absorbed by the liquid and gaseous oxygen in the tank. Were the heater probe temperatures to rise above about 500° F, the wire insulation in its proximity would begin to degrade.

A test simulating prolonged application of power to heaters and fans with a heater probe half immersed in liquid nitrogen at one atmosphere pressure was conducted at MSC. After 8 hours, a thermocouple mounted directly on the outer casing of a heater element at a location where it was in contact only with the gaseous nitrogen in the ullage indicated a surface temperature of about 1000° F. At the same time, the temperature of the conduit wall reached 735° F.

Posttest inspection of the wiring indicated that the insulation had been seriously degraded (fig. D3-24). The insulation had become relatively brittle and had cracked in numerous places. Upon any subsequent flexing of the wire, the insulation would either break off or shift to widen the cracks, in either case exposing the conductor. Such an exposure would set the stage for a future short circuit. The state and nature of the degradation of the insulation depends on the temperature it reaches. It should be noted that this test was conducted in a nitrogen atmosphere, whereas the actual prolonged heater operation occurred in an oxygen environment. An oxygen environment is less benign chemically than one of nitrogen, and greater degradation than that observed might occur. The all-up test at Beech should provide more definitive information on this matter.

In summary, the nonstandard detanking procedure probably provided the mechanism for initiating the flight failure by causing sufficient damage to wire insulation to expose the conductor(s) of the fan motor leads. This would permit a short circuit to occur and initiate combustion within the tank. It is also possible that some solder was melted during the prolonged heating. Under the normal gravity conditions on the launch stand, it would be possible for a drop(s) of solder to fall free and solidify and remain in the tank. This could possibly lead to the subsequent shorting of the capacitor gage.

Discussion

As described in the preceding sections, the design of the oxygen tank as a pressure vessel is very adequate. It is constructed of a tough material well chosen for the application. There is no evidence of substandard manufacture of the particular tank involved, nor has any evidence been found of subsequent damage that would result in degradation of the structural integrity of the pressure vessel (as distinguished from the internal components of the tank).

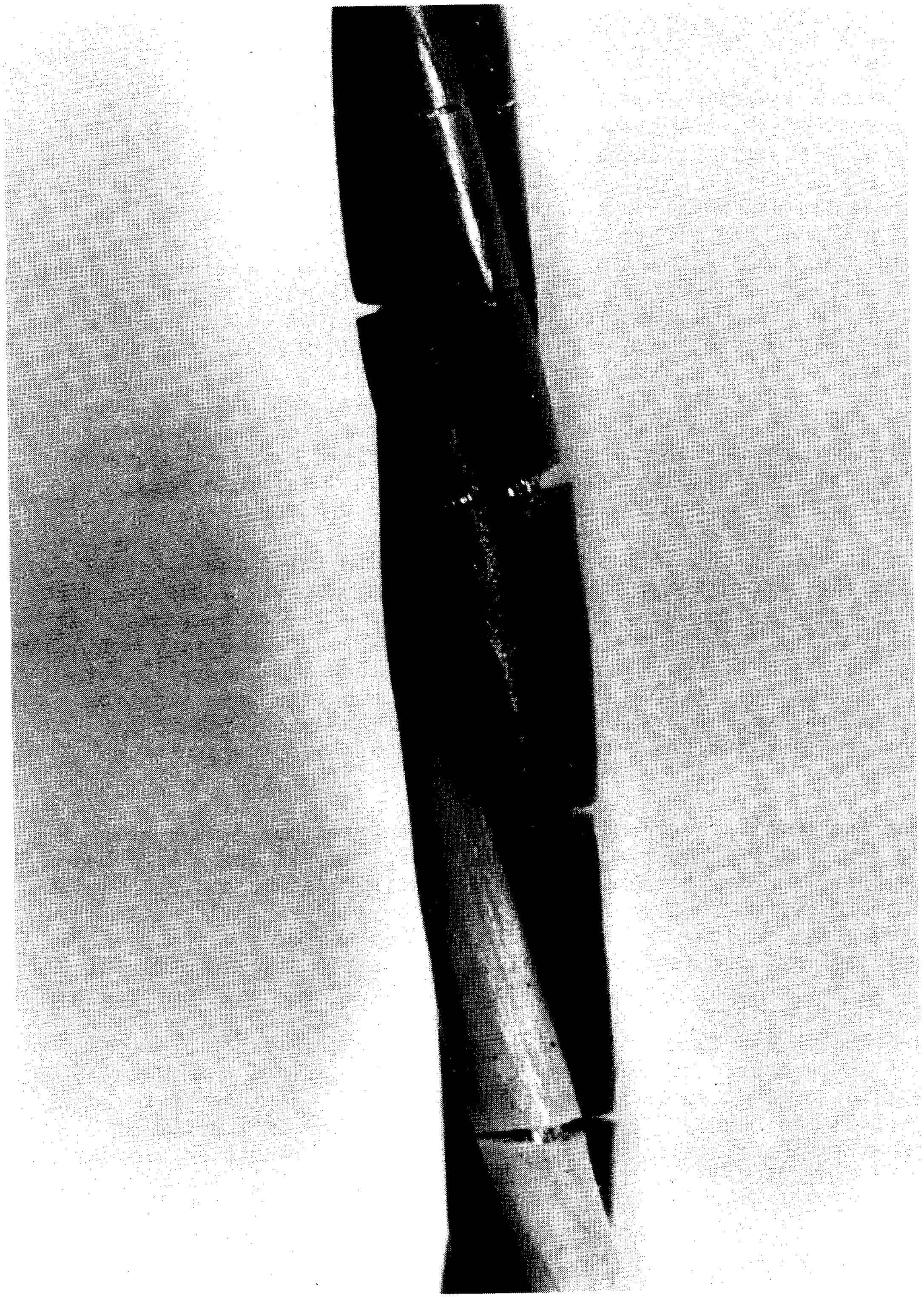

Figure D3-24.- Photograph of wire damage.

If the telemetered pressure data truly represent the pressure the tank experienced at the time of the accident, it should not have failed structurally. The qualification burst test results indicate that the pressure vessel is capable of withstanding over twice the maximum pressure indicated at the temperatures recorded. The tubing is capable of withstanding even greater loads.

There was, as described in Appendix B, an observed abnormal increase in pressure and temperature in the tank. As has been discussed previously, there are combustibles, both metallic and nonmetallic, within the tank, as well as potential energy sources to provide ignition, especially of the Teflon insulation of the internal wiring. The method of assembling the tank system and the details of construction of the tank's internal components provide an opportunity for wiring damage. Also, there is an even greater probability that, in this instance, the nonstandard detanking process created bare conductors. With such damaged wiring, a mechanism for creating a spark is provided and a consequence would be a fire within the confines of the tank. This would result in increases in the pressure and temperature within the tank.

There is sufficient Teflon within the tank to cause the internal pressure to rise above the burst strength of the pressure vessel were it all to be consumed. However, the locations of the Teflon components are such that igniting <u>all</u> of them is not very probable. The energy available from the combustion of the aluminum within the tank also exceeds that required to burst the tank. Tests conducted during the investigation indicate that enough electrical energy was available to initiate a combustion process within the tank under electrical fault conditions (Appendix F).

Among the possible ways that the tank integrity could have been lost, two are worthy of special mention. First, should combustion have existed within the electrical conduit, a relatively stagnant region with an intentionally poor heat conduction path, the conduit walls would have been heated quite rapidly. The conduit contains the greatest concentration of wiring and wire insulation within the tank. It was estimated that raising the conduit temperature to about 1500° F under the pressures prevailing during flight would cause the conduit walls to fail. This has subsequently been demonstrated in a test at MSC wherein the wiring insulation in an actual conduit was intentionally ignited under conditions simulating the conduit environment within the tank. In this test, local heating caused the conduit to fail a short time after initiation of combustion within the conduit. Such a failure would result in pressurization of the tank vacuum dome, leading to actuation of the blowout patch and loss of oxygen tank pressure.

The second possibility is associated with the reaction of aluminum with oxygen. This process has been described as quite violent (see Appendix F). Were the aluminum to have been ignited and if its reaction rate under the conditions within the tank were sufficiently high, the pressure could rise very rapidly and lead to pressure vessel failure at burst pressure levels. Such a pressure rise might not have been evidenced in the data because of the low sampling rate of the pressure sensor telemetry signal. Tests are required to verify this hypothesis.

A number of observations were made during the course of the Panel's activities that gave rise to further questions. It is recognized that many of these matters are of a subjective nature. Nonetheless, they are considered worthy of comment in this report.

Oxygen tank no. 1 lost pressure subsequent to the failure of tank no. 2. The mechanism of damage to tank no. 1 has not been established. It is assumed to be the result of a line or valve failure in the tank no. 1 system. The two tanks and their associated hardware represent, to a large degree, redundant systems. They are, however, in great part colocated. For example, the tanks are adjacent to one another, the system valves are grouped in a common housing, the fluid lines and wiring are routed parallel to one another in close proximity. Systems other than the oxygen subsystems have similar configurations. Such practice provides the possibility of inducing failure in a redundant system by a failure of its companion. This is a most complex subject and difficult to assess. It is also recognized that much of the hardware for Apollo has already been built. There appears to be a need for a review and evaluation of this matter.

No evidence has been found that indicates that shock testing of components and/or subsystem assemblies is a normal qualification requirement for Apollo service module hardware. The flight environment contains shocks of a considerable magnitude during events such as staging of the launch vehicle. That the effects of such environments on system components were recognized is evidenced by the use of holding current on the fuel cell reactant shutoff valves, for example. Shocks can be applied to hardware during shipment and normal handling, even though elaborate precautions in the form of special shipping containers, labels, and cautionary tags to alert transportation groups to the sensitivity of the shipment are employed. Good design and development practice includes experimental determination of margins against damage under such circumstances. Again, there appears to be a need for a review and evaluation of the susceptibility of the components in the spacecraft to all credible shock levels they may encounter in their service life so that the margins of safety inherent in their design may be established.

RELATED SYSTEMS

As a result of the Apollo 13 accident, a critical examination of other Apollo systems is being conducted by MSC to insure that the potential for a similar mode of failure does not exist elsewhere in the spacecraft. A member of the Design Panel was present at the MSC review meetings. The following is a summary of the activity and a status of the MSC effort.

The review was limited to selected systems in the following major Apollo elements:

Command and service module

Ascent and descent stage of the lunar module

Government furnished equipment

Ground support equipment

As an aid in determining which subsystems should be reviewed, a tabulation of all pressure vessels in these major elements was assembled (table D3-X). The cryogenic oxygen tank, which is reviewed in earlier sections of this report, was excluded from this review. Table D3-XI lists those systems and major elements that were selected for review. All vessels and oxygen and propellant line components in the selected systems are to be analyzed. The primary emphasis during the review is on the oxygen and oxidizer systems and the identification of all sources of energy--both internal and external to the system--that could result in an excessive pressure rise and possibly result in the failure or degradation of a system. Sources of energy which were considered were electrical, mechanical, and solar.

Pressure Vessels

The pressure vessels are of concern in that they represent large energy sources in the event of their catastrophic failure. Qualification records were reviewed and analyzed to determine the actual factors of safety demonstrated by burst test, as well as the characteristics of the failure modes. The failure modes of the pressure vessels have been categorized as explosive, uncertain, and benign. With these data, an assessment was made of those components that might be damaged by the explosion of a tank and the effect of this explosion on the vehicle systems and the crew.

TABLE D3-X.- PRESSURE VESSELS

Tank	System/location	Number	Normal operating pressure	Media	Material
Water	ECS/LM D/S	1	47.3	N_2/water	6061 T6 aluminum
GOX	ECS/LM A/S	2	890	Oxygen	718 Inconel
Water	ECS/LM A/S	2	27.3	N_2/water	6061 T6 aluminum
GOX	ECS/LM D/S	1	2690	Oxygen	D6aC steel
Oxidizer	Propulsion/LM A/S	1	184	Helium/N_2O_4	6Al-4V titanium
Helium	Propulsion/LM A/S	2	3050	Helium	6Al-4V titanium
Fuel	Propulsion/LM A/S	1	184	Helium/Aerozine 50	6Al-4V titanium
Helium	Propulsion/LM RCS	2	3050	Helium	6Al-4V titanium
Fuel	Propulsion/LM RCS	2	180	Helium/Aerozine 50	6Al-4V titanium
Oxidizer	Propulsion/LM RCS	2	180	Helium/N_2O_4	6Al-4V titanium
Helium	Propulsion/LM DPS	1	1640	Helium	6Al-4V titanium
Helium	Propulsion/LM DPS	1	400-1550	Supercritical helium	5Al-2 1/2 Sn titanium
Fuel	Propulsion/LM DPS	2	248	Helium/Aerozine 50	6Al-4V titanium
Oxidizer	Propulsion/LM DPS	2	248	Helium/N_2O_4	6Al-4T titanium
Battery	EPS/LM A/S	2	3-5	KOH/Ag-Zn	Magnesium
Battery	EPS/LM D/S	4	3-5	KOH/Ag-Zn	Magnesium
Battery	EPS/LM ED	2	15	KOH/Ag-Zn	Epoxy glass
Hydrogen	EPS/SM	2	225	Supercritical hydrogen	5Al-2 1/2 Sn titanium
Fuel	Propulsion/SM-SPS sump	1	186	Helium/Aerozine 50	6Al-4V titanium
Fuel	Propulsion/SM-SPS storage	1	186	Helium/Aerozine 50	6Al-4V titanium
Oxidizer	Propulsion/SM-SPS sump	1	186	Helium/N_2O_4	6Al-4V titanium
Oxidizer	Propulsion/SM-SPS storage	1	186	Helium/N_2O_4	6Al-4V titanium
Helium	Propulsion/SM-SPS	2	3600	Helium	6Al-4V titanium

TABLE D3-X.- PRESSURE VESSELS - Continued

Tank	System/location	Number	Normal operating pressure	Media	Material
Nitrogen	Propulsion/SM-SPS	2	2350	Nitrogen	AM 350 steel
Oxidizer	Propulsion/SM Primary RCS	4	186	Helium/N_2O_4	6Al-4V titanium
Oxidizer	Propulsion/SM Secondary RCS	4	186	Helium/N_2O_4	6Al-4V titanium
Fuel	Propulsion/SM Primary RCS	4	186	Helium/MMH	6Al-4V titanium
Fuel	Propulsion/SM Secondary RCS	4	186	Helium/MMH	6Al-4V titanium
Helium	Propulsion/SM RCS	4	4150	Helium	6Al-4V titanium
Oxidizer	Propulsion/CM RCS	2	291	Helium/N_2O_4	6Al-4V titanium
Fuel	Propulsion/CM RCS	2	291	Helium/MMH	6Al-4V titanium
Helium	Propulsion/CM RCS	2	4150	Helium	6Al-4V titanium
Battery	EPS/CM-entry	3	0-20	KOH/Ag-Zn	Epoxy laminate
Battery	EPS/CM-pyro	2	15	KOH/Ag-Zn	Epoxy glass
Nitrogen	EPS/SM-fuel cell	3	1500	Nitrogen	AMS 4910 titanium
Nitrogen	EPS/SM-fuel cell	3	53	Nitrogen	5Al-2 1/2 Sn titanium
Nitrogen	SIM/SM	1	4000	Nitrogen	6Al-4V titanium
Oxygen	ECS/CM-surge	1	900	Oxygen	718 Inconel
Oxygen	ECS/CM-repress	3	900	Oxygen	718 Inconel
Glycol	ECS/CM	1	50/18-27	Glycol/oxygen	6061 T6 aluminum
Potable water	ECS/CM	1	18/22 18/27	Water/oxygen	6061 T6 aluminum
Waste water	ECS/CM	1	18/18-27	Water/oxygen	6061 T6 aluminum
Accumulator	ECS/CM	2	100	Water/oxygen	6061 T6 aluminum
Fire extinguisher	Crew/CM	1	85	Water/freon 12	718 Inconel
Nitrogen	Hatch/CM	2	5000	Nitrogen	718 Inconel
Nitrogen	Probe/CM	4	5000	Nitrogen	718 Inconel

TABLE D3-X.- PRESSURE VESSELS - Concluded

Tank	System/location	Number	Normal operating pressure	Media	Material
Oxygen	PLSS	1	1020	Oxygen	301 cryoform
Water	PLSS	1	3.8	Water/oxygen	6061 T6 aluminum
Battery	PLSS	1	5-8	KOH/Ag-Zn	Titanium
Oxygen	OPS	2	5880	Oxygen	718 Inconel
Carbon dioxide	Raft	2	1000	CO_2	301 cryoform
Carbon dioxide	Life vest	2	1000	CO_2	Steel
Oxygen	PAD pack	5	3600	Oxygen	301 cryoform
Helium	Snap 27 fuel capsule	1	4-700	Helium	Haines 25
Helium/ nitrogen	Seismic experiment	1	333	10% helium 90% nitrogen	AM 347
Air	Crew/LGEC camera	1	500	Air	6061 T6 aluminum
Hydrogen	GSE/KSC	1	20	Liquid hydrogen	6061 T6 aluminum

TABLE D3-XI.- Subsystems Selected for Review by MSC

Command module

- Environmental control
- Reaction control
- Electrical power
- Mechanical

Service module

- Service propulsion
- Reaction control
- Electrical power

Lunar module ascent stage

- Environmental control
- Reaction control
- Ascent propulsion
- Electrical power

Lunar module descent stage

- Environmental control
- Descent propulsion
- Electrical power

Government furnished equipment

- Crew equipment
- Lunar surface experiments
- Scientific instrument module

Ground support equipment

- Hydrogen servicing dewar
- PAD emergency air pack
- High-pressure oxygen line components
- Oxygen/fuel line components with electrical interface

The explosive failure of a pressure vessel on the spacecraft, depending upon the energy stored in the vessel, could result in effects ranging from localized damage to loss of spacecraft and crew.

The following approaches were considered to provide protection to the spacecraft and crew from the catastrophic explosion of a major pressure vessel:

1. Isolation of the pressure vessel by separation.

2. Controlled failure provisions by changes to the vent or relief system to permit rapid depressurization.

3. Containing the blast by the addition of shielding by heavier or strengthened walls.

It was concluded that it would be theoretically possible to provide increased, but not total, protection for the spacecraft against the catastrophic explosive failure of a pressure vessel if major vehicular and pressure vessel changes were made. There are many practical limitations which preclude the provision of total protection against the catastrophic explosive failure of a pressure vessel. To determine the effect on the spacecraft of a nonexplosive or a benign leakage-type failure of a pressure vessel, the components and materials in the immediate vicinity of the tank in question were identified. Both the LM and CSM have nonmetallic materials which probably would not survive if they were exposed to propellants as the result of a pressure vessel failure. It is not feasible to use materials throughout the spacecraft which are totally compatible with all fluids that they could encounter following a primary failure. Considering the vehicle and systems effects of a pressure vessel failure (leakage or explosive), it is clear that neither containment nor complete nonmetallic material compatibility can be provided in the form of practical or reasonable solutions for spacecraft and crew protection against all tank failures. A tank failure would result in at least the abort of a mission, even through the damage from a pressure vessel could be contained.

The review of the pressure vessels of table D3-X identified a direct electrical interface or exposed wiring in the media as follows:

1. Propellant quantity gaging systems in the lunar module descent stage tanks and in the service module service propulsion system (SPS) tanks.

2. Capacitance gage, heaters, motors, and temperature sensor in the cryogenic hydrogen tanks in the service module.

3. Quantity gage in the potable and waste water tanks in the command module.

4. Quantity sensing gage in the GSE hydrogen dewar.

The MSC is conducting an analysis and plans to perform tests on the quantity gaging systems to insure that the combination of fuel and energy potential for ignition are understood and represent no hazard. Associated with this is a review of the circuitry and circuit protection. The waste and potable water tanks are being reviewed to determine the hazards, if any, of the electrical circuit and the advisability of deleting the quantity gage.

The cryogenic hydrogen gas pressure vessel was reviewed and it was verified that the manufacturing and assembly techniques, as well as the arrangement of the internal components, are very similar to those of the oxygen tank. The same potential for an electrical malfunction in the hydrogen tank exists as did in the oxygen tank. Mission rules have been reviewed and it was determined that the minimum failure in a hydrogen tank which would result in a mission abort would be the loss of two heaters and one fan. The MSC is planning to conduct tests to determine if an electrical malfunction can induce a sustained reaction between hydrogen and materials contained within the tank. Tests will also be conducted to determine if both heaters would fail following an electrical malfunction. Structural and materials compatibility analysis and reviews indicate that the titanium alloy (5 Al, 2-1/2 Sn) as used does not experience hydrogen embrittlement.

The remaining pressure vessels were reviewed to determine those that had internal components, which could expose an electrical interface to the contained media following a single failure. In addition, the nonmetallics that might be exposed following such a single failure are being identified to insure that they are compatible with the media at operating conditions.

The review of the LM pressurized tanks disclosed that helium and oxygen tanks are isolated from their relief valves during the translunar coast period. Under normal flight conditions at ambient temperatures the pressure rise in the tanks is relatively insignificant. If protective thermal blankets on the LM should be lost or damaged, the pressure rise could be significant. A Grumman study indicates that if the complete loss of thermal blankets occurred in the areas of the following tanks they could reach burst pressures during translunar coast:

Ascent stage oxygen

Ascent propulsion system helium

Reaction control system helium

Descent propulsion system helium

Loss or damage of a thermal blanket could probably be determined during transposition and docking on all except the descent helium tank. It should be noted that no rational failure mode has been identified which could result in the loss or damage of a thermal blanket.

Line Components

The line components that are integral to the systems in table D3-XI are also being examined to determine those with and those without an electrical interface. The electrical interfaces are of two types, direct exposure to the media and exposure following a single failure. In addition, all nonmetallics near a potential ignition source will be identified and evaluated.

The only component which has been identified as of this date as having nonmetallics and a direct electrical interface in high-pressure oxygen is the fuel cell reactant shutoff valve. The Teflon-coated wires internal to this valve, when energized, carry steady-state currents of 2 amperes and transients of 10 amperes in a 900 psi oxygen environment. The circuit protection consists of a 10-ampere circuit breaker. During the launch and boost phase, a current limited circuit, approximately 0.5 ampere at 9 to 10 volts, is applied to the "open" coil to insure that the valve remains in the open position. The valve position sensor switch, which is also internal, is continuously energized during the entire mission from a 28-volt circuit protected by a 10-ampere breaker. This valve is now the subject of an intensive review by MSC and the contractor. There is no indication that this reactant valve had any internal malfunction during the Apollo 13 accident other than the shock closure.

Components without direct electrical interfaces are also being examined to identify those in which nonmetallic materials are normally exposed to the media and those in which nonmetallic materials could be exposed following a single failure. To determine the probability of a single failure in static components such as temperature and pressure transducers, the acceptance and certification testing of critical elements is being reviewed. It has been ascertained that component elements such as bellows, probe cases, and internal diaphragms are designed and tested for pressure levels far in excess of system usage. The reliability reports confirmed that leakage failure of these elements has not occurred on Apollo flight hardware.

In addition to normal material compatibility determinations, those components which have nonmetallics used in impact applications are being identified and it is planned that, where necessary, additional testing will be conducted in the media at appropriate operating conditions to determine that there are no impact-sensitive applications.

Low Pressure Oxygen Systems

Following the Apollo 204 accident, the metallic and nonmetallic materials in the cabin of both the command module and lunar module were subjected to an intensive review. As a result of the research and testing, the materials within the LM and CM were modified or changed to reduce the probability of an ignition and to minimize the combustion or propagation of fire in the cabin. Considering the redesign that was accomplished and the continuing rigorous control of materials added to the spacecraft cabins, the low-pressure oxygen systems (less than 25 psi) were not reevaluated during this current investigation by MSC.

Electrical Power System--Batteries

Both the LM and the CSM use the same type battery to initiate the pyrotechnic functions. A review of the records indicated that the G-10 laminated glass epoxy battery case had not been qualified as a pressure vessel. The case is protected by a relief valve which operates at 30 ± 5 psi. In the event of a relief valve failure, and case pressurization to rupture, potassium hydroxide could be released. A certification program will be conducted to establish the strength of this battery case and procedures established for the acceptance proof testing on all flight batteries prior to each mission.

Ground Support Equipment

This review is structured to identify all pressure vessels and line components in propellant and high-pressure oxygen systems with direct electrical interfaces and the associated metallic and nonmetallic materials. All high-pressure oxygen, gaseous and liquid, valve seat material will be identified as well as any other application of nonmetallic material in an impact loading application. This MSC review is limited to equipment supplied by North American Rockwell and Grumman.

During the review of the GSE, it was also established that cleaning and filtering techniques used have been generally effective in limiting contamination. Shock-sensitive materials have been detected in the liquid hydrogen dewar in small quantities (less than 1 mg/liter), which are within specification limits for nonvolatile residuals. The source and quantity of the shock-sensitive materials should be identified, as well as the potential for a buildup in concentration. It is recognized that contamination is not considered as a candidate cause for the Apollo 13 accident.

Certification

The certification records for all pressure vessels and components of the subsystems that were considered have been reexamined during this MSC review. It was established that all certification requirements were adequately met, that all discrepancies were adequately explained, and that all components were qualified for flight. It should be noted that a comparison of the certification requirements with the expected flight and ground environment was not part of this review.

Apollo J-Missions

Both the CSM and LM systems are being modified to support the extended lunar stay time and lunar orbit experiments for later Apollo missions. The MSC review included the nitrogen bottle being added to the scientific instrument module of the service module for the Pan camera. The other system changes and additions to the LM and CSM for the J-Mission consist of the addition of more pressure vessels and components of the types already installed in the spacecraft and examined during this review. No new pressure vessels or components are planned.

Lunar Module "Lifeboat"

Associated with the Related Systems Review, MSC is also analyzing how the "lifeboat" capability of the LM could be enhanced. The LM, CSM, and PLSS/OPS are being reviewed to determine what minor modifications to the concerned systems and/or changes in procedures should be incorporated. The intent of the changes would be to enhance the ability of the crew to interchange or transfer oxygen, water, electrical power, and lithium hydroxide cannisters between spacecraft and to increase the probability of crew survival following multiple failures in the command module.

DISCUSSION

As a result of the MSC Related Systems Reviews that have been completed and are still in progress, the following observations are offered.

A fracture mechanics analysis was made of all Saturn-Apollo pressure tanks by the Boeing Company for NASA in 1968-1969 (ref. 40). However, most of these tanks were designed without consideration of fracture mechanics. Consequently, at the time of the Boeing analysis, some pertinent data were not available. For example, sustained load and cyclic load flaw growth data were not available for Inconel 718 electron beam welds such as are used in the supercritical oxygen tanks and in the GOX tanks of the LM ascent stage. These data are now being generated in a current program at Boeing, sponsored by NASA. It is also understood that sustained load flaw growth data are not available for a D6aC steel GOX tank in the LM descent stage. Until very recently (ref. 41) sustained load flaw growth data were not available for the cryoformed 301 GOX tanks used in the PLSS and the PAD pack. It is entirely possible that the new data will not change the conclusions derived from the original fracture mechanics analysis; however, it is advisable to reexamine the Boeing analysis of the spacecraft pressure vessels with a view to incorporating the latest information. As an example, particular attention is warranted for the 6Al-4V-Ti tanks containing nitrogen tetroxide, since nitrogen tetroxide is a potentially aggressive environment for titanium. It is recognized that elaborate precautions are presently being taken to control the service conditions of these tanks in such a way that sustained load crack growth should not occur during a mission.

To assure that no unsatisfactory materials are used in oxygen/oxidizer systems in future spacecraft, it is advisable to examine all components and/or elements for compatibility (including dynamic applications) in their media. Where compatibility data at the appropriate service conditions are not available, tests should be conducted.

It appears appropriate to conduct tests with typical hydrogen tank materials in hydrogen, at system operating conditions, to determine if an exothermic reaction can be initiated by electrical fault.

It would be appropriate to expand the MSC investigation to include a review of the manufacturing processes used in the fabrication of critical tanks and components to insure that the processes used are not conducive to inducing failures.

A reevaluation of the filtration, sampling, and analysis of the gases and fluids used is considered appropriate to insure that the requirements for cleanliness and purity in the servicing of spacecraft systems are being satisfied.

It may be advisable to conduct investigations of the compatibility of the nonmetallics in the launch vehicle oxygen and oxidizer systems, as well as spacecraft and launch vehicle GSE (with emphasis on impact sensitivity at operating conditions).

PART D4

SUMMARY

The Design Panel conducted a review and evaluation of the design of those elements of the Apollo spacecraft systems that were implicated as contributing to the Apollo 13 accident. These comprise primarily the oxygen tanks of the service module, the associated valves, plumbing, and electrical systems. In addition, the Panel surveyed other systems within the spacecraft to determine whether their designs contained potential for failures similar to those of the oxygen tank.

During its considerations, the Panel examined the tank in two configurations. The first was in the configuration as defined by the drawings and other controlling documentation. The second configuration was what might be termed the "as flown" condition, that is, containing such variations from standard as may have resulted from unusual events in the history of oxygen tank no. 2. The following were the two most significant such events:

1. The oxygen "shelf drop" incident during spacecraft manufacture.

2. The unorthodox detanking procedure employed at KSC made necessary by inability to detank in the standard manner.

The following observations result from this review:

1. As a pressure vessel, that is, from a structural viewpoint, the tank is adequately designed. The pressure vessel is constructed of a tough material well chosen for this application. The stress analyses and results of the qualification burst test program confirm the ability of the tank to exhibit adequate structural performance in its intended application.

2. From a systems viewpoint, the design of the oxygen tank is unsatisfactory. The design features of the tank system are such that:

(a) It is difficult to install the internal components of the tank. The design is such that this operation is "blind" and not amenable to visual inspection after completing the installation.

(b) There is power wiring internal to the tank exposed to supercritical oxygen.

(c) There is great potential for damage to internal wiring during assembly. There are sharp corners on metal parts in proximity to the wires; the wiring is routed over rather tortuous paths; the wiring is located in close proximity to rotating components and to the heater elements; and the wiring is free to be flexed by moving fluid during fan operation and/or during filling or emptying of the tank with gaseous or liquid media.

(d) The rating of the thermostats in the heater circuits is not compatible with the voltages that are (and in this instance were for a prolonged period) applied to these circuits at the launch site.

(e) There are combustible materials within the tank, such as Teflon, solder, aluminum, and drilube 822.

3. The combination of combustible materials and potential ignition sources, including the use of unsealed electric motors, constitutes a hazard that can lead to a fire within the tank.

4. The manufacturing tolerances of the Teflon adapters, short Inconel tube, and quantity gage center tube that comprise the tank fill and drain tube are such that extremely loose fit can occur. If these elements were at or near the appropriate dimensional extremes in tank no. 2, it is possible that mechanical shock could cause a disengagement of these parts that could have led to inability to detank. Such might have been caused by the "shelf drop" incident.

5. The nonstandard detanking of oxygen tank no. 2 at KSC probably led to the degradation of the insulation of the internal wiring. The insulation probably became brittle, and flexing of the wire either during or subsequent to the detanking could cause it to break off, exposing the conductor. This would provide a means for creating an electrical short that could initiate combustion of the insulation. The planned all-up test reproducing the detanking should provide data to conclusively verify this.

6. The fuel cell oxygen shutoff solenoid valve has power wiring and combustibles exposed to a 900 psi oxygen environment and is protected by a 10-ampere circuit breaker. The combination of combustibles, potential ignition source, and oxygen within this device constitutes a hazard similar to that prevailing within the oxygen tank.

7. The caution and warning indicators in the CM for the fuel cell reactant shutoff valves use series logic. This logic requires that both the hydrogen and oxygen reactant valves be closed in order that a warning indication may be given. Therefore, it is possible for a fuel cell to be deprived of one of its reactants because of a closed valve and thus suffer irreversible damage without the crew being made aware of this state via the caution and warning indicators.

8. Loss of a main bus deprives some of the talkback indicators of actuating power. In such an eventuality, misinformation as to the state of certain valves may be presented to the crew when valid information as to status of system components is most vital.

9. The logic of the master alarm feature of the caution and warning system is such that preexistence of an operationally expected signal (within a given subsystem) such as "hydrogen pressure low" prevents receipt of a master alarm for a second, and possibly dangerous, condition such as high oxygen pressure.

As a result of these observations, it is the consensus of the Design Panel that the Board should give consideration to including the following among its recommendations.

The internal components of the oxygen tank system should be redesigned. The requirement for the functions performed by these components should be reevaluated carefully. If it is determined that some or all of these components are mandatory for accomplishing the mission, the redesign should be of such nature as to minimize the amount of potentially combustible material within the tank. The installation of any wiring that must be within the tank should be so designed as to preclude direct contact with the oxygen if at all possible. As a minimum, wiring must not be in contact with the oxygen if, under fault conditions, sufficient energy is available to ignite proximate materials. Determination of what constitutes sufficient energy for ignition should be based on data from tests conducted under all conditions that would be encountered in service. It would be preferable that any redesign of the internal components permit assembly of these components into a total subsystem outside the tank. This would permit thorough inspection and test prior to installation within the pressure vessel.

The fuel cell reactant shutoff valve should either be redesigned to eliminate electrical wiring in contact with high-pressure oxygen or a suitable substitute valve be found.

The logic of the caution and warning system should be reviewed with a view towards eliminating lack of a warning indication for a single malfunction that can cause irreparable loss of a mission-critical component. The logic of the master alarm feature of the caution and warning system should also be reviewed with the view towards eliminating the feature that precludes the receipt of a second alarm in the presence of a preexisting alarm from the same system or subsystem. The possibility of providing a redundant power supply to permit proper functioning of talkback type indicators in the event of loss of the main bus normally supplying power to the indicators should also be examined with a view to providing a valid indication to the crew in the event of such a malfunction.

The ability of components to perform their appropriate functions without damage when exposed to shock loading levels in excess of those anticipated to be encountered in flight or in ground handling should be demonstrated by tests. Components found wanting in this respect should be either modified or replaced.

The comprehensive review initiated by the MSC Apollo 13 Investigating Team of all CSM and LM tanks, valves, and associated system elements in which oxygen or oxidizers are stored, controlled, or distributed should be prosecuted vigorously. The acceptability of materials within such components should be established by tests conducted under fluid conditions like those that will be encountered in service both on the ground and in flight. In addition, the review should be expanded to include the manufacturing and assembly procedures employed in the fabrication of those of the previously noted components which are determined to contain hazards.

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